Semnan University

Mechanics of Advanced Composite Structures

journal homepage: http://MACS.journals.semnan.ac.ir

Microstructure, Mechanical and Electrical Properties of Copper Matrix Composites Reinforced with Steel Nanoparticles

V. Norouzifard [a*], H. Naeinzadeh [b], A. Talebi [c], Z. Ebrahimi [b]

[a] *Department of Mechanical Engineering, Jundi-Shapur University of Technology, Dezful, P.O.B. 64615334, Iran*
[b] *Mechanical Engineering Department, Payame Noor University, Iran*
[c] *South Rouhina Steel Complex (SRSC), Dezful, Iran*

KEYWORDS

Metal matrix composite
Steel nanoparticles
Impact energy
Electrical conductivity

ABSTRACT

In this study, copper matrix composites reinforced by 2.5, 5.5, and 8 wt% steel nanoparticles less than 130 nm in diameter were prepared by the casting method. The steel nanoparticles were made of steel machining chips. Disc mill and ball mill instruments were used to produce nanoparticles from machining chips. Copper was melted using an induction furnace, and the steel nanoparticles were injected into the copper melt by gas gun. The nanoparticle content effect on microstructure, mechanical properties, fracture toughness, and electrical conductivity of the composites are investigated in this paper. Increasing the reinforcement content to 2.5 wt% in the produced composite increases the yield strength, tensile strength, and ductility by 20%, 49%, and 13%, respectively, and then the strengthening effects deteriorate. By increasing the nanoparticle content, elongation and ductility almost continuously increase. Maximum elongation and Charpy impact energy of 90 J and 37% are achieved in this research for the composite grade reinforced by 8 wt% of steel nanoparticles that these values are almost 8.2 and 1.2 times greater than impact energy and elongation of the pure copper sample. Furthermore, the addition of steel nanoparticles shows a little adverse effect on the electrical conductivity but dramatically improves the composite toughness.

1. Introduction

In recent years, demand for materials with high electrical and thermal conductivity and good mechanical properties has increased within electronic and manufacturing industries. Pure copper is a high electrical and thermal conductive material, but mechanical strength is the Achill's heel of components made of pure copper. Copper reinforcing has minor effects on the pure copper electrical and thermal conductivities compared to other strengthening methods like alloying. Therefore, copper matrix composites [1–13] have attracted considerable interest in recent years to overcome pure copper mechanical shortcomings. In electronics, heat exchanger, aerospace, and automotive industries the copper matrix composites have been chiefly used [14].

Ceramic [2, 6, 7, 10, 11, 13, 15, 16], metal [1, 17–20], and recently carbon nanotube [5, 12] and graphene [9, 21] have been used as reinforcement to produce copper matrix composites. Alumina [2, 3, 7] and silicon carbide [10, 15, 16] are used in most commonly copper matrix ceramic particulate composites due to their high hardness and resistance, refractory nature, and relative availability, and low cost. However, fabrication of ceramic reinforced copper matrix composites using conventional casting methods results in poor mechanical and physical properties because of poor wettability between ceramic particles and molten copper and undesirable chemical reaction at their interface [6, 10]. As a result, agglomeration of ceramic particles and weak interface bonding between the particles and matrix diminishes proper load transfer from matrix to

* Corresponding author. Tel.: +98-91-24396001; Fax: +98-61-42426666
Email address: vnorouzi@jsu.ac.ir

DOI: 10.22075/MACS.2021.20783.1272
Received 20-07-02; Received in revised form 21-05-11; Accepted 21-11-15

reinforcement particles and adversely affects mechanical properties and thermal and electrical conductivities [1]. There are two common solutions proposed to improve the distribution uniformity of particles in the copper matrix and the interface bonding; using powder metallurgy technique and coating the surface of the ceramic particle with special materials [1, 6, 15].

Several efforts have also been made to reinforce copper using carbon nanotubes (CNTs) [5, 12] and graphene nano-platelets (GNPs) [9, 21]. Limitations on the availability of high-quality CNTs in large quantities, the tendency of CNT/ GNP reinforcements to agglomeration within the copper matrix, poor copper/reinforcement interface bonding, and high cost of the complex technologies utilized in the composite production process are the main obstacles for using CNTs and GNPs to fabricate copper matrix composites with desired mechanical properties in large industrial quantities.

Comparing the materials mentioned above, metal-based reinforcements have relatively good wettability with the copper matrix. Zhou et al. [20] investigated high-strength copper/steel composite wires fabricated by rod-in-tube technology. Using high plastic deformation and heat treatment, Zhou et al. [20] achieved a strength level of more than 1 GPa for the copper composites. Grunberger et al. [17, 18] also used a similar procedure to reinforce copper wires with pearlitic and high nitrogen stainless steel. Alaneme and Odoni [1] used steel machining chips as reinforcement particles in the copper matrix and investigated the produced composite's mechanical properties, wear, and corrosion behavior. According to the results of Alaneme and Odoni's [1] research, using steel particles as reinforcement improves copper mechanical strength without significantly decreasing its toughness.

The literature review enlightens that using steel particles to produce the copper matrix composite can be led to the following advantages; good wettability of the particles in the matrix, the possibility of using simple and inexpensive manufacturing processes like conventional casting methods, availability and low cost of reinforcement materials, and feasibility of composite components' mass production. In this study, copper matrix composites reinforced by 2.5, 5.5, and 8 wt% steel particles with spherical shape and less than 130 nm size were prepared. According to the machining mechanics, the machining chip has ultrafine-grained microstructure due to the high shear plastic deformation, which increases the strength and hardness of the chip [1]. Therefore, the steel particles were produced from steel machining chips by mechanical method. Disc and ball mill machines were used to change the machining chips' shape and size. Microstructure, mechanical and electrical properties of the produced copper matrix composites were investigated.

2. Experimental

2.1. Materials

Pure commercial copper (99.9%) served as the matrix of produced composites in this work. The reinforcement nanoparticles were made of discontinuous machining chips produced during the turning of the AISI 430 steel bars. The chemical composition of the steel bars measured by emission spectrometry is listed in Table 1.

2.2. Steel powders fabrication

Disc mill (RS 200) and ball mill (PM 400) machines converted the steel chips to steel powder. Steel particles with an average size of less than 10μm were fabricated from the chips using a disc mill machine. To refine 300 grams of the steel chips, the machine worked for 20 minutes at a speed of 800 rpm. Then, a planetary ball mill machine was used to produce steel nanoparticles with an average size of about 130 nm from the disc mill machine product. The following parameters were set for the ball mill machine; type and size of balls: tungsten balls with different sizes, a ball to powder ratio of 10:1, milling speed: 200 rpm, and total working time of 22.5 hours that divided to 30 minutes periods containing 20 minutes working and 10 minutes rest times. The procedure parameters were set based on the values proposed in the literature. Some try and error experiments also were performed to adapt the parameter values for the present case. Stearic acid was added to the particles to prevent the cold welding of the steel particles during the ball milling operation. After several repetitions, the acid to the particles mass ratio 1:50 was found to be suitable.

Table 1. Chemical composition of the steel nanoparticles

Elements	Weight %
Fe	Base
C	0.085
P	0.015
S	0.0214
Cr	15.34
Ni	0.23
Co	0.0041
V	0.0034
W	0.0016
Pb	0.0024
Sn	0.00075

2.3. Composite fabrication

The casting method was used to produce the copper matrix composites. A coreless induction furnace was utilized to melt copper and mix the steel nanoparticles. Copper bars with a diameter of 22 mm were put in the furnace for about 20 minutes to melt completely. The proper amount of the steel particles required to produce composites having 2.5, 5.5, and 8 wt% reinforcement particles based on the furnace charge was injected into the copper melt using a gas gun. To preheat the steel nanoparticles and prevent oxidation, hot Argon gas is served in the gas gun to transport the nanoparticles to the melt. As known, the melt is stirred in the induction furnace because of the interaction of the applied magnetic field with eddy currents in the melt. Therefore, the nanoparticles will be distributed in the copper melt using a coreless induction furnace due to the mentioned stirring mechanism during the melt preparation.

The casting molds were made of low-carbon steel. A cavity with a dimension of 60*140*12 mm was made on the molds. The molds were preheated at a temperature of 300 °C. To prevent melt adhesion, the mold surfaces in contact with the melt were covered by boron nitride. Solidified composite samples were put for one h in a heat treatment furnace at a temperature of 850 °C to perform the homogenization on the microstructure of the samples.

2.4. Composite samples characterization

Microstructure investigation of the produced composite samples was performed using Mira 3-XMU field emission scanning electron microscope (FE-SEM). Tensile and impact tests were carried out to study the mechanical behavior of the composite samples. Charpy impact test was performed on a Zwick-Roell impact machine based on the ASTM E23 standard [22]. Impact test specimen perpetration and testing procedure were conducted according to the mentioned ASTM standard. Tensile properties of the composites were also assessed by a Schenck-Trebel testing machine at room temperature and a strain rate of 3×10^{-3} s^{-1}. Specimen configuration, testing procedure, and tensile properties determination followed ASTM E8/E8M standard [23].

3. Results and discussion

3.1. Microstructure

Figure 1 shows an SEM micrograph of the prepared copper matrix composite reinforced by 2.5 wt% nanoparticles. Two light and dark fields with recognizable color contrast are seen in the micrograph. The darkfield shows the copper matrix, while the light phases are the nanoparticles.

SEM micrograph of the composite sample containing 5.5 wt% of nanoparticles is also shown in Fig. 2. The micrograph illustrated in Fig. 2 was prepared with higher magnification to present the reinforcement particles better. Figure 3 shows a micrograph of the composite sample having eight wt% of nanoparticles with the same magnification as Fig. 1. The increased number of steel nanoparticles from Fig. 1 to Fig. 3 is in proportion with the increase of the particles' weight fraction in the samples of the SEM micrographs. The average size of three representative particles is presented in Fig. 3. The presented particle dimensions show that the reinforcement particles size is less than 130 nm.

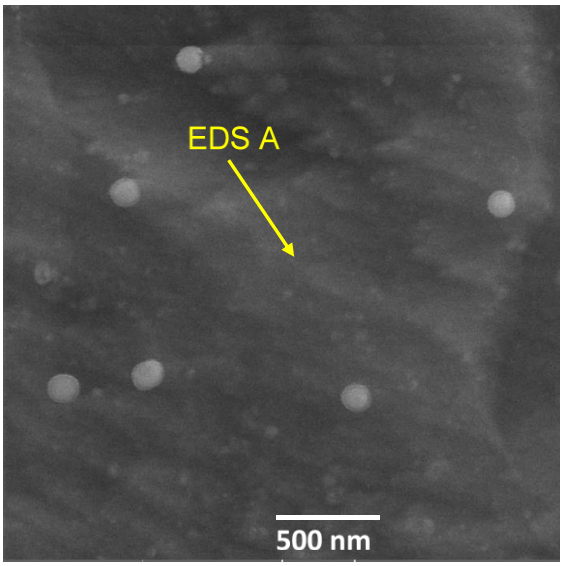

Fig. 1. SEM micrograph of copper matrix composite reinforced by 2.5 wt% steel nanoparticles

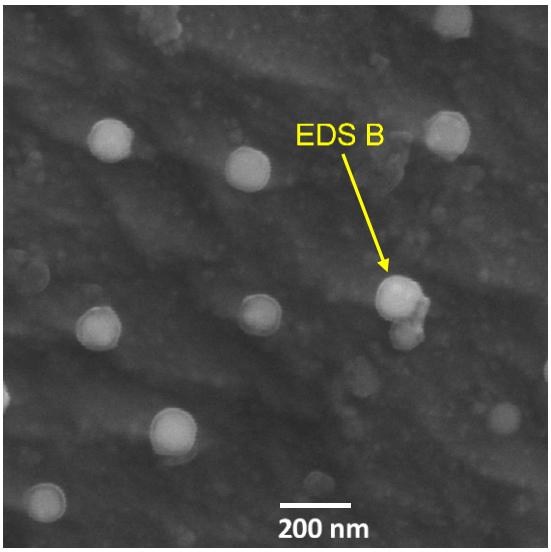

Fig. 2. SEM micrograph and of copper/5.5 wt% steel nanoparticles.

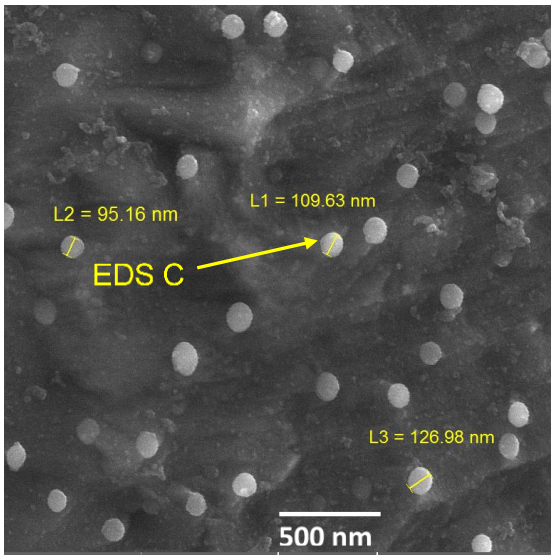

Fig. 3. SEM micrograph of copper matrix composite reinforced by eight wt% steel nanoparticle

According to the presented SEM micrographs, the steel particles have a quasi-spherical shape in the prepared composite samples. As known, the shape of the reinforcement particles can affect composite material's mechanical properties, especially fracture toughness.

EDS profiles of the composite samples were also provided, as shown in Fig. 4. The position of the EDS analysis of each sample is shown in the SEM micrographs (Fig. 1, 2 & 3). EDS analysis of the composite reinforced by 5.5 and 8 wt% steel particles is performed nearby the particles. Nevertheless, for the composite with 2.5 wt% particles, an area far from the reinforcement particles is selected. Thus, Figs. 4b and 4c show the EDS profile of the area consisting of the matrix and the nano-particles, while Fig. 4a shows the matrix profile. Peaks of copper (Cu), iron (Fe), carbon (C), and chromium (Cr) are seen in the EDS profiles of Figs. 4b and 4c confirm the presence of copper and AISI 430 steel in the composite sample. The absence of oxygen peak in the EDS profiles (Fig. 4a, b & c) also demonstrates that the steel particles oxidation did not occur during the composite production.

The EDS quantitative results of the elements' weight percent and atomic percent are also illustrated in Fig. 4. Comparing the content of the element from the EDS analysis of the matrix shown in Fig. 4a with the 99.9% pure copper used as matrix material shows that the purity of the copper decreased about 0.5 wt% during the composite production process.

Considering the iron and chromium content in EDS results of Figs. 4b and 4c, the chromium content in the steel nano-particles can be estimated by dividing the chromium wt% by the sum of the iron wt% and chromium wt%. Values of 16.6% and 14.8% are calculated for the chromium wt% in the steel particles from EDS results of Figs. 4b and 4c, respectively. The calculated values are in agreement with the steel nano-particle composition (Table 1).

The composite samples' microstructure is also investigated by SEM-EDS mapping. Figure 5 shows SEM-EDS maps of the composite grade containing 5.5 wt% steel particles. The iron and chromium elements exhibit the reinforcement particles distribution in the copper matrix. Almost similar maps are observed for the 2.5 and 8 wt% grades with different total numbers and distribution of elemental points.

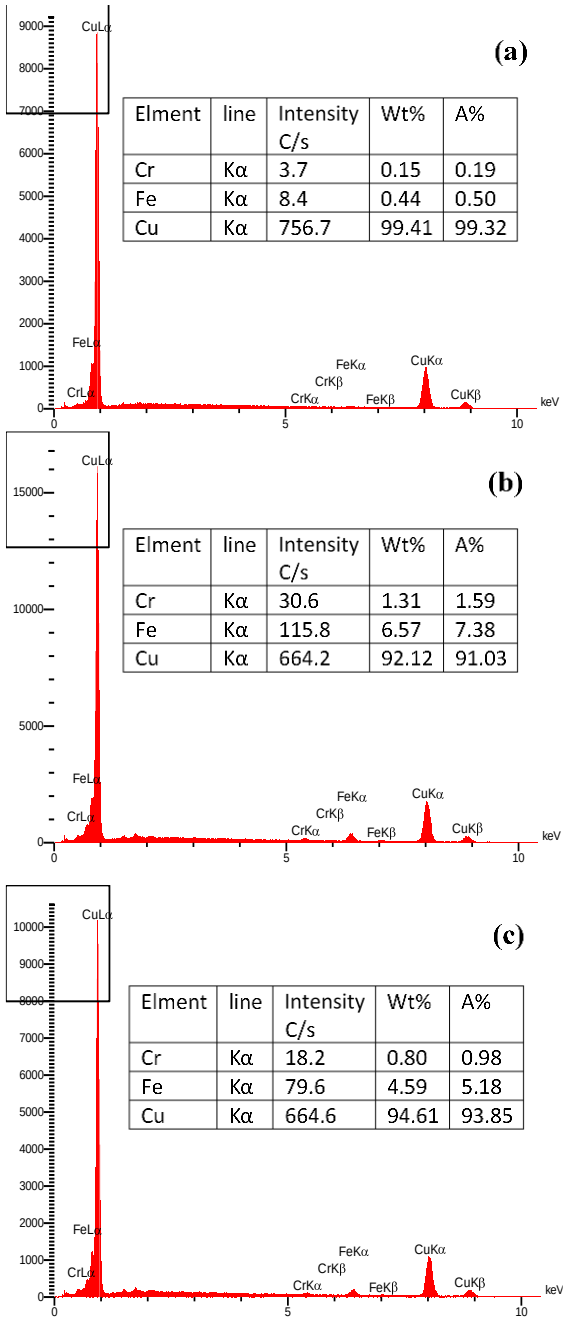

Fig. 4. EDS profiles and quantitative results from copper matrix composites reinforced by a) 2.5, b) 5.5, and c) 8 wt% steel nanoparticles

Figure 6 shows the X-ray diffraction analysis result of the composite with eight wt% of steel particles. The profiles related to steel particles are not seen due to the low volume fraction and dispersion of the steel particles. There are similar XRD results in the literature in which the reinforcement particles are not detected in the metal matric composites with low reinforcement content. For example, Bagheri [24] investigated the properties of copper matrix composites reinforced with TiC particles, and all TiC peaks have been visible in the XRD results of the composite with more than 20 vol. % TiC particles.

3.2. Tensile test results

Figure 7 shows the engineering stress-strain diagrams of the composites reinforced by 2.5, 5.5, and 8 wt% nanoparticles. For comparison, the stress-strain curve of pure copper prepared by the same production process of the composites is also presented in Fig. 7. Tensile tests were conducted on three specimens for each composition, and one of them is illustrated in Fig. 7.

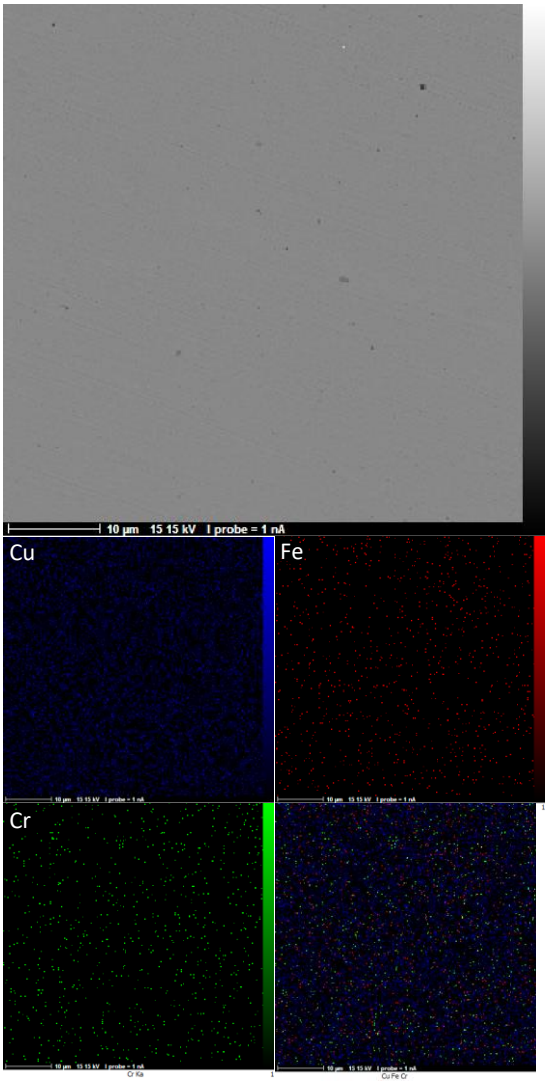

Fig. 5. SEM-EDS elemental maps of the copper matrix composites reinforced by 5.5 wt% steel nanoparticles

Tensile properties variation versus the steel particle content of the composite grades is illustrated in Fig. 8. Based on the tensile test results, adding 2.5 wt% of the steel reinforcement to the copper matrix increases tensile strength, yield strength, and elongation of the produced composite by 20%, 49%, and 13%, respectively. While adding more reinforcements and increasing the steel nanoparticles content to 5.5 and 8 wt% adversely affect the composite's tensile strength and yield strength.

The yield strength first increases to 121 MPa at the nanoparticle content of 2.5 wt% and when the particle content increases to 5.5 wt%. Finally, the yield strength further decreases to 83 MPa at the nanoparticle concentration of 8 wt%, which is slightly higher than the pure copper sample yield strength. According to Fig. 8, the tensile strength of the produced composites rises to 238 MPa by adding 2.5 wt% nanoparticles to the pure copper, and then by increasing the particles weight fraction, the tensile strength decreases continuously until the nanoparticle content reaches eight wt%.

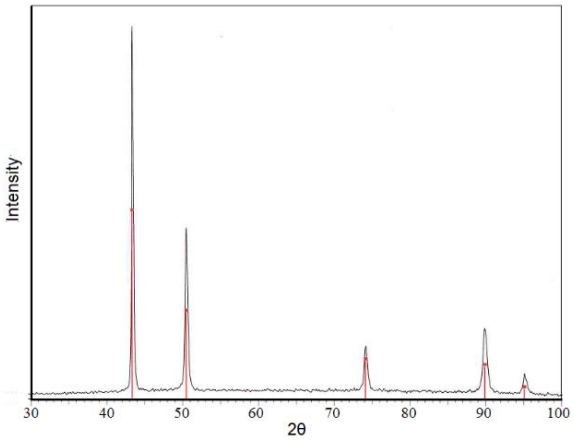

Fig. 6. XRD profile of the copper matrix composites reinforced by eight wt% steel nanoparticles

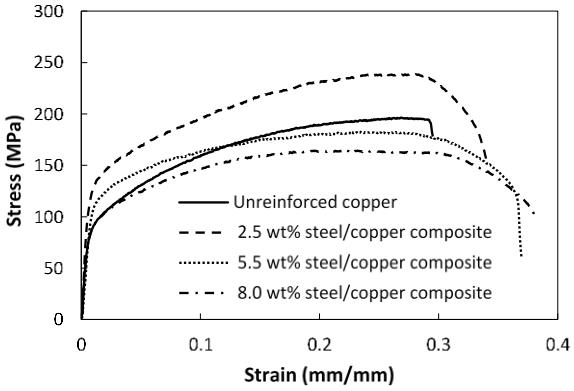

Fig. 7. Stress-strain curves of pure copper and copper composites reinforced by 2.5, 5.5, and 8 wt% steel nanoparticles

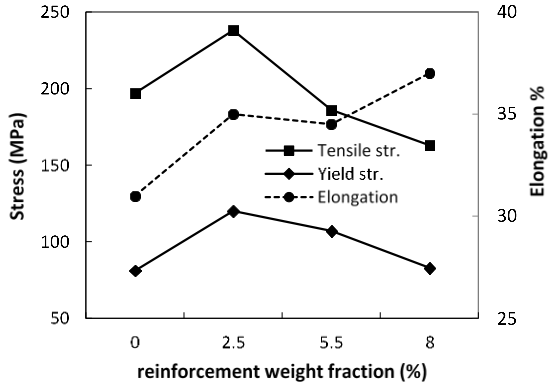

Fig. 8. Tensile strength, yield strength, and elongation of pure copper and copper composites reinforced by 2.5, 5.5, and 8 wt% steel nanoparticles

Based on the recent literature [6], increasing the weight fraction of reinforcement particles, especially uncoated ceramic particles, increases porosity resulting from the agglomeration of the reinforcements. Agglomeration is known as a reason for undesirable mechanical properties of metal matrix composites. To determine the porosity of the composite samples following procedure was performed on each sample. The composite specimen density was measured by Archimedes' principle using a digital scale with a resolution of 0.0001 gr. Then, the composite theoretical density was calculated considering copper and steel density and the steel particle concentration in the composite. Finally, porosity in the composite specimens is achieved by:

$$\rho_T = f_{cu}.\rho_{cu} + f_{st}.\rho_{st} \tag{1}$$

$$porosity = \frac{\rho_T - \rho_{Ex}}{\rho_T} \times 100\% \tag{2}$$

where, ρ, f are density and volume fraction. Indices *cu*, *st*, *T* and *Ex* refer to copper, steel particles, theoretical and experimental, respectively. The volume fraction of the steel particles in the composite samples can be calculated by the particle weight fraction and the steel and copper densities. Values of 0.0284, 0.0623, and 0.0903 are calculated for the volume fraction of the steel particles for composite grades containing 2.5, 5.5, and 8 wt% reinforcement particles, respectively.

Tensile strength, yield strength, and porosity of the pure copper and composite grades are listed in Table 2. The porosity of the present copper matrix composites is less than 0.54%. According to the composite grades porosity listed in Table 2, porosity decreases by increasing the reinforcement weight fraction. Therefore, it seems that porosity has a small impact on reducing the yield and tensile strengths in the composite grades reinforced by 5.5 and 8 wt% nanoparticles.

To better understand the produced composite strength variation versus the nanoparticle content, it is necessary to investigate the effects of the reinforcement particles on the matrix strength. There are three common strengthening effects. The first one is Orowan strengthening mechanism, which is given by the Orowan-Ashby equation [25]

$$\Delta\sigma_{Orowan} = \frac{0.13 G_m b}{\lambda} \ln\left(\frac{d}{2b}\right) \tag{3}$$

where G_m and b are shear modulus and the Burgers vector of the matrix. d and λ are the average diameters of the particles and the average interparticulate distance between the reinforcement particles, respectively.

The second strengthening mechanism comes from the coefficient of thermal expansion (CTE) mismatch between the particles and the matrix. The composite materials strengthen by the CTE mechanism because of increasing dislocation density in the vicinity of the particles during the cooling process. The dislocation density, ρ, can be calculated by [26];

$$\Delta\sigma_{CTE} = \eta G_m b \sqrt{\frac{12\Delta\alpha\Delta T f}{bd\left(1-f\right)}} \tag{4}$$

where η is a constant and Δα is the difference in the particles and matrix coefficients of thermal expansion. The thermal expansion coefficient of copper and AISI 430 steel at room temperature are 15.4×10^{-6} and 10.5×10^{-6} 1/°C, respectively, and then the value of Δα should be 4.9×10^{-6} 1/°C. ΔT is the difference between the last heat treatment temperature (homogenization for the present samples) and the test temperature, 850 and 25 °C, respectively.

Table 2. Porosity measurement results and mechanical strength of the produced composites

Sample composition	Theoretical density (gr/cm3)	Experimental density (gr/cm3)	Porosity (%)	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)
Pure copper	8.96	8.8917	0.7622	81±1	197±2	31±3
Cu- 2.5 wt% St.	8.9322	8.8798	0.5452	121±1	238±1	35±0.5
Cu- 5.5 wt% St.	8.8987	8.8588	0.36	107±11	186±3	34.5±2.5
Cu- 8 wt% St.	8.8709	8.8459	0.1566	83±2	163±1	37±5

The last strengthening mechanism is the load-bearing effect. The strong bonding between the particles and matrix causes that reinforcement dispersed particles bear part of the applied load on the composite. For the equiaxed particulates, the load-bearing contribution of reinforcements is given as [27]

$$\Delta\sigma_l = 0.5f\ \sigma_m \quad (5)$$

where σm is the yield strength of the matrix because the distance between the reinforcement particles in the matrix decreases by reducing the diameter of the particles, Orowan strengthening mechanism is one of the effective strengthening mechanisms of the nanocomposites.

Although the thermal expansion mismatch between copper and steel particles is considerably lower than the mismatch between copper and the nonmetallic reinforcements, the nano size of the steel particles causes that the CTE mechanism increases the strength of the composites. The load-bearing mechanism has the lowest effect on the strength of the present composites because of the low volume fraction of the steel particles. The maximum load-bearing effect on the composite flow stress can be 4.5% of the matrix flow stress in the composite grade containing eight wt% steel particles.

According to Equations 3 to 5, the effect of all three strengthening mechanisms on the composite flow stress should increase by increasing the steel particles' volume fraction. Therefore, the yield and tensile strengths of the composites are expected to be increase theoretically by adding more steel particles to the matrix. However, tensile test results of the present composite samples show a decrease in the mechanical strength of the composite when the steel particles content increases from 2.5 to 8 wt%.

Figure 9 shows an SEM micrograph of the composite sample reinforced by eight wt% steel particles in a lower magnification than Fig. 3. As seen, in some regions (arrow with solid line), the particles are either aggregated or located so close together. On the other hand, some regions (arrow with dashed line) remain unreinforced and have no steel particles. Therefore, by increasing the steel particle content, the composite mechanical strength can be adversely affected due to the following reasons. Firstly, increasing the unreinforced areas decreases the matrix load-bearing average area strength. Secondly, the aggregated particles cause discontinuity and microcracks, which weaken the matrix. Finally, the matrix material between the closely located particles is highly strained during heat treatment operation, and mechanical loading and microcracks can be developed in the matrix.

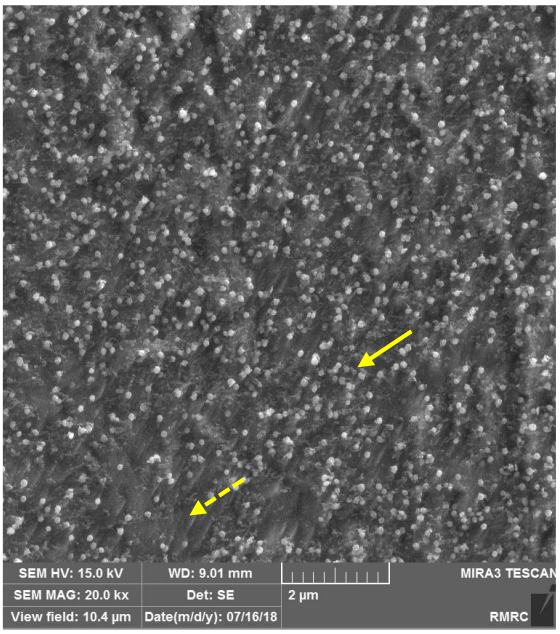

Fig. 9. SEM micrograph of copper matrix composite reinforced by eight wt% steel nanoparticles

The mechanical strength reduction in composites with 5.5 and 8 wt% steel particles can be justified by the mentioned weakening mechanisms.

Figure 8 also shows the present composite grades fracture point elongation. Elongation and, as a result, ductility of the copper/steel nanoparticle composites first increases by increasing the weight fraction of the nanoparticles to 5.5 wt% and then increases by a further increase of the particle content up to 8 wt%. In a metallic matrix, when a crack meets reinforcement nanoparticles that are properly bonded to the matrix, the crack cannot continue its previous path, and it should turn around the particle to pass unless the particle itself splits. However, fracture of the reinforcement particles can happen in brittle particles like ceramics. Therefore, in the present composites, spherical nanoparticles prevent crack propagation in the matrix, and ductility of the reinforced material increases by increasing the particles' weight fraction to 2.5 wt%. As mentioned before, adding more particles increases the possibility of particle aggregation, and the number of micro-cracks results from thermal expansion mismatch. Thus, the ductility of the produced composites decreases slightly when the particle content increases from 2.5 to 5 wt%. Finally, the unreinforced regions (see Fig. 9) increase by increasing the steel particles, and the high plastic deformation of these regions increases elongation.

Figure 10 shows the fracture surface of the composite and pure copper tensile test samples. The variation of the plastic deformation of the samples before the final fracture versus the

reinforcement particles content shows the same trend as presented by the elongation.

3.3. Impact test results

Figure 11 shows Charpy impact test results conducted on the pure copper and the composite grades. As seen in Fig. 11, the energy absorbed by the composite specimens is considerably higher than pure copper. Adding 2.5 wt% nanoparticles to the copper matrix, the pure copper Charpy impact energy rises three times. As mentioned above, the steel nanoparticles in the copper matrix can block the crack path and increase crack tip plastic deformation. Thus, more energy is consumed to deform the fracture area plastically. From 2.5 wt% to 5.5 wt% nanoparticle content, considerable change is not seen in the Charpy energy diagram (Fig. 11) except moderately decreasing. The reduction in the Charpy energy of the composite sample reinforced by 5.5 wt% particles can be related to a decrease in the composite mechanical strength and ductility. Comparing the Charpy test results with the elongation of the tensile test specimens (Fig. 8), an almost similar trend can be found between them. Increasing the steel particles weight fraction to 8 wt%, the Charpy impact energy sharply rises. An increase in dislocation density at the front of a crack tip can facilitate plastic deformation of the crack tip, and it is blunting [28], and the material shows more toughness.

On the other hand, the distance between the nanoparticles decreases when the nanoparticle content increases. As mentioned before, the crack should turn around the reinforcement particles when it meets one of them. Thus, the nanoparticles can stop the crack propagation if the distance between particles becomes less than a critical value. Therefore, the high Charpy impact energy of the composite grade reinforced by eight wt% nanoparticles can be related to increasing the number of the nanoparticles that act as obstacles in the crack path and increasing dislocation density around the particles.

Figure 12 illustrates a schematic of the Charpy impact test fracture surface according to ASTM E23 [22]. The fracture surface consists of four regions: the crack initiation region below the notch, the shear lip region near the specimen side edges, the final fracture region on the opposite side of the notch, and the unstable fracture region in the center. In the unstable fracture region, radial marks can be seen, pointing to the crack initiation region.

The fracture surfaces of the prepared composite specimens were also studied using an RZ-BD Meiji stereo microscope. Figure 13 shows the micrographs of the fracture surfaces.

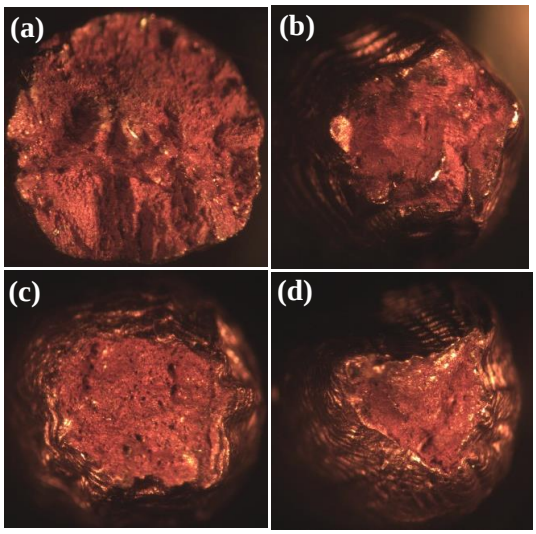

Fig. 10. Tensile test fracture surfaces of a) pure copper and copper composites reinforced by b) 2.5, c) 5.5, and d) 8 wt% steel nanoparticle

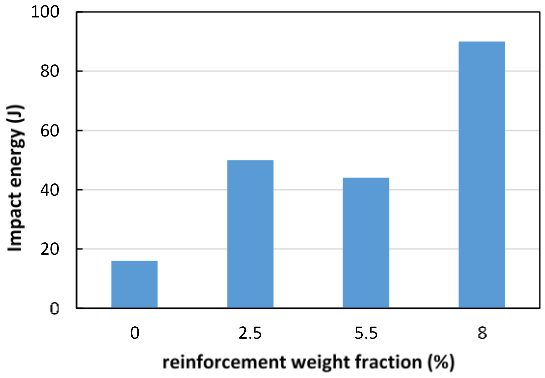

Fig. 11. The Charpy impact energy of pure copper and copper composites reinforced by 2.5, 5.5, and 8 wt% steel nanoparticles

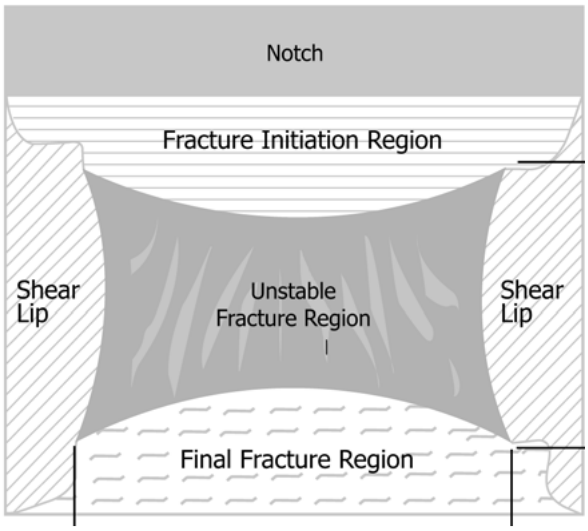

Fig. 12. Schematic of the Charpy fracture surface [22]

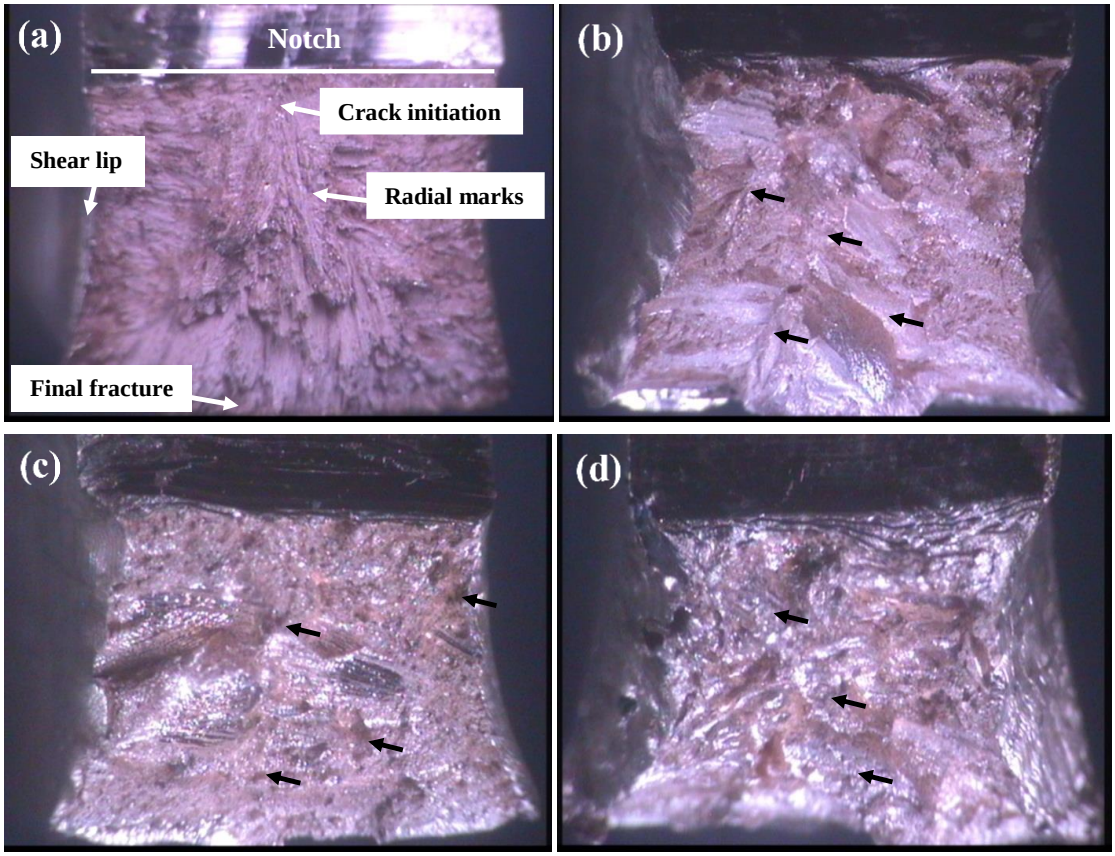

Fig. 13. Fracture surfaces of a) pure copper and copper composites reinforced by b) 2.5, c) 5.5, and d) 8 wt% steel nanoparticles

As seen in Fig. 13a, the fracture surface of pure copper has a narrow shear lip in the specimen sides, and the radial marks can be seen in the center. Narrow shear lips and radial marks indicate that the ductile fracture percent of the present pure copper sample is low, which confirms the small impact energy of the sample. In the fracture surface of the copper composite samples reinforced by nanoparticles (Fig. 13b, c, and d), the radial marks cannot be seen in pure copper. Large and curved shear lips in the composite samples' fracture surface (Fig. 13b, c, and d) indicate a ductile fracture of the samples. Increasing the content of the particles from 2.5 wt% (Fig. 13b) to 5.5 wt% (Fig. 13c), the sheer lip regions are moderately shrunk. Therefore, the ductile fracture decreases from the composite grade with 2.5 wt% particles to 5.5 wt% particles. As seen in Fig. 13d, among the composite grades, the largest shear lip region belongs to the composite reinforced by eight wt% nanoparticles, which indicates a high percentage of ductile fracture and confirms its high impact energy. The samples' ductile fracture variations versus the reinforcement content agree with the impact energy results (Fig. 11).

3.4. Electrical conductivity

Figure 14 shows the electrical conductivity of the prepared pure copper and composite grade samples. As expected, adding steel nanoparticles decreases the electrical conductivity of pure copper due to the steel's low electrical conductivity compared to copper. According to Fig. 14, the electrical conductivity of the composite containing 2.5 wt% nanoparticles is at least 92% of the reference copper conductivity. However, even when the steel particles' weight fraction increases to 8 wt%, the electrical conductivity of the produced composite is still more than 88% of the reference copper. Therefore, adding up to 8 wt% steel particles to the copper matrix did not seriously change the electrical conductivity of copper.

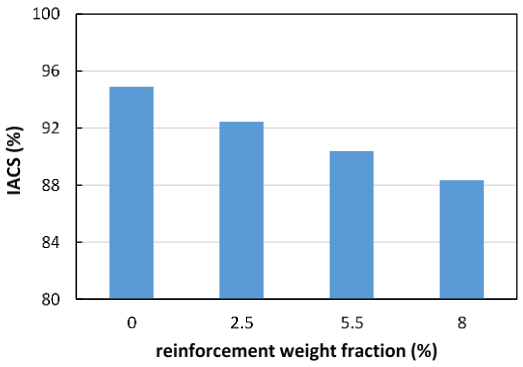

Fig. 14. Electrical conductivity of pure copper and copper composites reinforced by 2.5, 5.5, and 8 wt% steel nanoparticles

4. Conclusion

Copper matrix composites were prepared to contain 2.5, 5.5, and 8 wt% steel nanoparticles as reinforcement. The nanoparticles were made from steel machining chips. SEM microscopy of the produced composites showed that reinforcement nanoparticles had been distributed properly in the matrix. EDS profile of the composite samples confirmed the presence of the steel and copper in the composite and indicated no oxidation in the steel nanoparticles. Tensile test results demonstrated that adding 2.5 wt% steel particles to the copper matrix improves yield strength, tensile strength, and ductility of produced composite. Mechanical strengthening of the composites was deteriorated by adding more reinforcement content than 2.5 wt%. However, ductility and fracture toughness still were increased by adding the nanoparticles. Electrical conductivity was gently decreased by increasing the nanoparticles concentration in the composite. Therefore, copper matrix composites reinforced by steel nanoparticles have a huge potential to be considered an alternative to pure copper in manufacturing electrical contact components. However, further researches are necessary to investigate the effects of the nanoparticles' chemical composition, reinforcement's weight fraction, etc., on the mechanical and electrical performance of the produced composites to achieve optimum condition.

References

[1] Alaneme, K.K. and Odoni, B.U., 2016. Mechanical properties, wear and corrosion behavior of copper matrix composites reinforced with steel machining chips. *Engineering science and technology, an international journal*, 19(3), pp.1593-1599.

[2] Shehata, F.A.R.O.U.K., Fathy, A., Abdelhameed, M. and Moustafa, S.F., 2009. Preparation and properties of Al2O3 nanoparticle reinforced copper matrix composites by in situ processing. *Materials & Design*, *30*(7), pp.2756-2762.

[3] Travitzky, N.A., 1998. Microstructure and mechanical properties of alumina/copper composites fabricated by different infiltration techniques. *Materials Letters*, *36*(1-4), pp.114-117.

[4] Safari, F., Khosroshahi, R.A., and Zolriasatein, A., 2017. Wear behavior of copper matrix composites reinforced by γ-Cu5Zn8 nanoparticles. *Powder Technology*, *318*, pp.549-557.

[5] Abolghasem, M., Rashidi, A., Abbasi, S.M. and Mihanpanah, M., 2013. Manufacture and mechanical properties study of copper-matrix nanocomposites reinforced with carbon nanotubes using powder metallurgy. *emergencias*, pp.22-27.

[6] Moustafa, S.F., Abdel-Hamid, Z. and Abd-Elhay, A.M., 2002. Copper matrix SiC and Al2O3 particulate composites by powder metallurgy technique. *Materials Letters*, *53*(4-5), pp.244-249.

[7] Fathy, A., Shehata, F., Abdelhameed, M., and Elmahdy, M., 2012. Compressive and wear resistance of nanometric alumina reinforced copper matrix composites. *Materials & Design (1980-2015)*, *36*, pp.100-107.

[8] Chrysanthou, A. and Erbaccio, G., 1995. Production of copper-matrix composites by in situ processing. *Journal of Materials Science*, *30*(24), pp.6339-6344.

[9] Chen, F., Ying, J., Wang, Y., Du, S., Liu, Z. and Huang, Q., 2016. Effects of graphene content on the microstructure and properties of copper matrix composites. *Carbon*, *96*, pp.836-842.

[10] Tjong, S.C. and Lau, K.C., 2000. Tribological behaviour of SiC particle-reinforced copper matrix composites. *Materials Letters*, *43*(5-6), pp.274-280.

[11] Peng, L., 2007. Fabrication and properties of Ti3AlC2 particulates reinforced copper composites. *Scripta materialia*, *56*(9), pp.729-732.

[12] Uddin, S.M., Mahmud, T., Wolf, C., Glanz, C., Kolaric, I., Volkmer, C., Höller, H., Wienecke, U., Roth, S. and Fecht, H.J., 2010. Effect of size and shape of metal particles to improve hardness and electrical properties of carbon nanotube reinforced copper and copper alloy composites. *Composites Science and Technology*, *70*(16), pp.2253-2257.

[13] Shojaeepour, F., Abachi, P., Purazrang, K. and Moghanian, A.H., 2012. Production and properties of Cu/Cr2O3 nano-composites. *Powder Technology*, *222*, pp.80-84.

[14] Kaczmar, J.W., Pietrzak, K. and Włosiński, W., 2000. The production and application of metal matrix composite materials. *Journal of materials processing technology*, *106*(1-3), pp.58-67.

[15] Köck, T., Brendel, A. and Bolt, H., 2007. Interface reactions between silicon carbide and interlayers in silicon carbide–copper metal–matrix composites. *Journal of Nuclear Materials*, *362*(2-3), pp.197-201.

[16] Pelleg, J., Ruhr, M. and Ganor, M., 1996. Control the reaction at the fiber-matrix interface in a Cu/SiC metal matrix composite by modifying the matrix with 2.5 wt.% Fe. *Materials Science and Engineering: A*, *212*(1), pp.139-148.

[17] Grünberger, W., Heilmaier, M. and Schultz, L., 2002. High-strength, high-nitrogen stainless steel–copper composite wires for conductors in pulsed high-field magnets. *Materials Letters*, *52*(3), pp.154-158.

[18] Grünberger, W., Heilmaier, M. and Schultz, L., 2001. High-strength pearlitic steel–copper composite wires for conductors in pulsed high-field magnets. *Materials Science and Engineering: A*, *303*(1-2), pp.127-133.

[19] Hamada, A.S., Khosravifard, A., Kisko, A.P., Ahmed, E. and Porter, D.A., 2016. High-temperature deformation behavior of a stainless steel fiber-reinforced copper matrix composite. *Materials Science and Engineering: A*, *669*, pp.469-479.

[20] Zhou, R., Embury, J.D., Wood, J.T. and Smith, J.L., 1996. High-strength, high-conductivity copper-steel composite. *Materials characterization*, *37*(5), pp.239-243.

[21] Tang, Y., Yang, X., Wang, R. and Li, M., 2014. Enhancement of the mechanical properties of graphene–copper composites with graphene–nickel hybrids. *Materials Science and Engineering: A*, *599*, pp.247-254.

[22] ASTM, E.2., 2016. Standard test methods for notched bar impact testing of metallic materials. *E23-2016, Pennsylvania, PA, USA*.

[23] ASTM, E8/E8M, 2016, Standard test methods for tension testing of metallic materials. *Pennsylvania, PA, USA*.

[24] Bagheri, G.A., 2016. The effect of reinforcement percentages on properties of copper matrix composites reinforced with TiC particles. *Journal of Alloys and Compounds*, *676*, pp.120-126.

[25] Turcsanyi, B., Pukanszky, B. and Tüdõs, F., 1988. Composition dependence of tensile yield stress in filled polymers. *Journal of Materials Science Letters*, *7*(2), pp.160-162.

[26] Arsenault, R.J. and Shi, N., 1986. Dislocation generation due to differences between the coefficients of thermal expansion. *Materials Science and Engineering*, *81*, pp.175-187.

[27] Nardone, V.C., and Prewo, K.M., 1986. On the strength of discontinuous silicon carbide reinforced aluminum composites. *Scripta Metallurgica*, *20*(1), pp.43-48.

[28] Saeidi, N. and Ekrami, A., 2010. Impact properties of tempered bainite–ferrite dual-phase steels. *Materials Science and Engineering: A*, *527*(21-22), pp.5575-5581.